**The Japan Society of Applied Physics Fall Meeting at the end of August is historically always held away from Tokyo. This year the venue was Fukuoka University. Of the 6000 or so participants, graduate students used the gathering to develop presentation skills; their mentors for networking and fusing alignments for research plans; and hardened industrial researchers as an opportunity for discussions with their colleagues and competitors during breaks between lectures. This review concentrates on reports, discussion and trends related to electronic devices fabricated using III-V semiconductors and carbon nanotubes.**

# Japan talks trends on III-Vs & carbon nanotubes

Professor Sumio Iijima, Meijo University, gave an invited talk during the Physics and Applications of Carbon Nanotubes session, to an audience eager for clues about future trends in the field from the man who made the 'accidental' discovery of CNTs in 1991. Professor Iijima noted that "CNT based nanotechnology is not an industry yet, but holds tremendous potential." Examples of new areas to watch are single-wall carbon nanotubes filled with fullerene buckyballs ('nano pea-pods') and metallofullerenes for storage devices; 'nano-horns', which due to their large surface area could be used as lubricants, gas absorption, fuel cells and as phage display libraries in the biotechnology sector.

In the regular CNT sessions, a noticeable trend is the increase in activities related to the synthesis of CNT by heating silicon and silicon carbide substrates, eliminating the requirement to use metal catalysts, with Denso Corp reporting the observation of CNT formation on the Si surface of an n-6H-SiC substrate heated to 1400°C.

With the fabrication of CNT-bipolar devices in mind, Tohoku University and Sony Materials Ltd reported success in the use of organic molecules (tetracyanoquinodimethane, (TCNQ) and tetrakis(dimethylamino)ethylene, (TDAE)) for doping SWNTs n and p-type. This was done by heating CNTs and organic molecules together in a glass vessel under a vacuum of $10^{-6}$ Torr. Fujistu Ltd has been engaged in using CNT for via hole filling and described the use of diamond mechanical polishing (diamond particle diameter of 30µm for via hole of 2µm) for producing flat surfaces for large area via hole connections.

The observation of hysteresis in CNT channel FETs has also become a new feature of recent reports on CNT- FET resear-ch in Japan, several university groups speculating the origin of this effect is due to water vapour between the CNT and oxide layers in back gated structures. Other reports on device related applications of CNTs included their use as alcohol sensors from Mitsubishi Chemical Co, and interconnects from Mitusbishi Electric Corp and NTT Basic Research Labs.

## Reports on CNT related devices

*Deposition of brush like CNTs by CVD using helium & acetylene gas mixture:* Hitachi Zosen Co Ltd.
*Use of magnetic & electric fields aligning SWCNTs in gel*: Mitsui Chemicals Inc.
*Electroless plating of CNT on Ni substrates for low contact connections*: Fujitsu Ltd.
*Field Emission Devices using carbon nanocoils:* Osaka Pref. University.
*Analysis of I-V hysteresis in CNT and peapod FETs:* Nagoya University
*Effect of defects on the I-V hysteresis of CNT FETs:* AIST
*Use of FIB milling and in situ W deposition for fabricating CNT FET nano devices:* Nagoya University, Dept Chem.
*Effect of water on the drain current of CNT FET and sensor applications:* Mitsubishi Chemical Company.
*Opening of CNTs by heating (500°C) and exposure to 1kPa of oxygen in a vacuum chamber*: Fujitsu Labs. Ltd.

Reports on 'traditional' III-V ultra high speed devices, such as GaAs/AlGaAs heterostructures, are scarce despite tremendous commercial activity in Japan.

"There is little to report in this field. Compared with the mid 1980's, the technology is mature and we are more concerned with cutting costs and increasing sales than research," was a reason given by an industrial engineer working on production of GaAs/AlGaAs HEMT wafers for a Japanese conglomerate.

However, there were some reports. Sumitomo Electric Inds, described the use of 'only wet chemical etching' for fabricating InP/InGaAs DHBTs. The resulting 1.1x5.6 micrometer DHBT devices showed ft=124 GHz, fmax=167 GHz, with a uniformity of 1.4GHz and 2.8GHz, over 3" wafers. Fujitsu Ltd is still endeavoring to extend the performance of HEMT and reported on the fabrication of a pseudomorphic channel InGaAs/InAlAs HEMT (gate length of 30nm) with a gm 1.5 S/mm and fT=547 GHz.

As the summaries show, there is an increase in III-V quantum dots and devices, with universities taking the initiative and InAs the flavour of the season.

## Reports on III-V quantum dots & devices

*Electrical transport properties of InAs QD for SET device applications:* Fujitsu Labs Ltd.
*Droplet hetero-epitaxy for fabricating InAs quantum dots in an InP matrix by LP-MOCVD in (001)InP substrates:* Nagoya University.
*Self assembly of InAs QD chains on GaAs (001) substrates by solid source MBE:* University of ElectroComs
*Coulomb blockade in InAs QDs:* University of Tokyo.
*Droplet hetero-epitaxy for fabricating InAs quantum dots in an InP matrix by LP-MOCVD in (001)InP substrates*: Nagoya University.

As expected there were several reports on high power AlGaN/GaN HEMT devices. Mitsubishi Electric Corp described the use of a 5 minute, 600°C rapid thermal anneal to reduce the leakage of Schottky gates of AlGaN/GaN HEMT devices. The 'off voltage' is improved from 105V to 178V, for a HEMT with maximum drain current of 1A/mm and $g_m$ of 140mS/mm. A group from Tokushima University fabricated low resistance ohmic contacts to GaN HEMT by depositing a 100nm layer of ZnO on AlGaN followed a metal layer of either Ti-Al or Ti-Al-Ni-Au. An anneal at 500°C yielded a resistance of 0.1 ohm mm.

Several groups are growing GaN HEMT on Si substrates to reduce manufacturing costs. Furukawa Electric Co reported AlGaN/GaN HFET grown on 2" Si(111) substrates by MOCVD showing stable operation at 300°C for up to 100H. Sanken Electric, a major power supply manufacturer, fabricated 3.57 $mm^2$ AlGaN/GaN devices (gate length 2.5 µm, source-drain separation of 16µm, gate width of 60mm) on Si (111) substrates for large current operation. The devices showed $g_m$=2.6S at more than 10A currents. Nagoya University reported on the growth of AlGaN/GaN HEMT on 4" Si substrates by MOCVD. The structures showed sheet carrier density of $1x10^{13}$ $cm^{-2}$ and mobility of ~1000 $cm^2$/Vs, at room temperature. The wafers have a surface roughness of 1.28 RMS, which is the same as similar structures grown on sapphire substrates. Researchers at NTT Basic Research Labs are working on GaN/InGaN DHBTs grown by MOCVD on SiC substrates. The characteristics of a device with an emitter size of 50µm x30 µm, showed a maximum current of 5.3 kA /$cm^2$ at collector-emitter voltage of 50V, which is a output power of 270kW/$cm^2$.

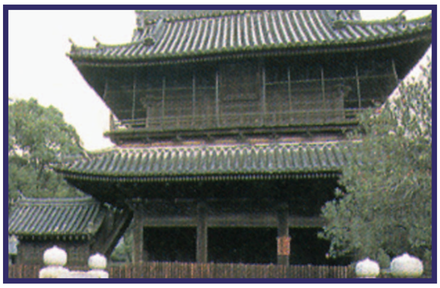
## Reports on GaN power devices

*Use of ultra thin aluminum oxide passivation layers reducing current collapse in AlGaN/GaN HFET*: Hokkaido University.
*Fabrication of a GaN HEMT (gate length= 0.21µm) with recessed gates grown by MOCVD on SiC substrates with a high transconductance of 525mS/mm.* Oki Electric Industry Co Ltd.
*Use of field plate for fabricating high breakdown voltage GaN HEMT*: Toshiba Corp. Semiconductor Co.
*Electrical DC characterisation of AlGaN/GaN HEMT (gate length=2 micrometers; 300K mobility=1320 $cm^2$/Vs; Ns=8.4x $10^{12}cm^{-2}$) grown on 100mm sapphire substrates by MOVPE, yielded devices with $g_m$=196.5 mS/mm*: Nagoya Inst. of Tech.
*AlGaN/GaN HEMT with a 35nm gate length exhibiting $f_T$=110 GHz at Vds=4V:* Fujitsu Labs. Ltd.
*Mass production of AlGaN/GaN HEMT & GaN substrates:* Hitachi Cable Ltd.
*Aluminium oxide/silicon nitride insulating gate channel doped AlGaN/GaN heterojunction FETs (gate length 1.5 micrometers) exhibiting transconductance of 160 mS/mm and maximum current density of 1.8A/mm*: NTT Photonics Lab, and BRL.
*Large scale production of AlGaN/GaN HEMT of 100mm sapphire substrates:* Powdec Ltd.

## Trends

An increasing number of companies are relying on government funding for basic research, indicating that industry is more cautious about investing in research without well defined commercial applications. The CNT research by Fujitsu Ltd and SiGe MOSFET by Toshiba Corp are two examples of government funded research being carried out by industry. Outsourcing of III-V wafer production is becoming more common. Even major companies cannot afford to carry out device development from scratch. This has led to an increase in the number of enterprises providing specialised services to such companies.

*Fukuoka City, on the island of Kyushu, Western Japan is 90 minutes flight from Haneda Airport, Tokyo. Fukuoka is known for the Shofukuji Temple, the first Zen temple in Japan build in 1195.*



*Fukuoka is also famous for the open air food stalls or yatai in the Nakasu entertainment district; the Daiei Hawks baseball team; and for the gourmets, Karashi Mentaiko, a spicy Cod Roe eaten with rice.*

The automobile industry will be a large market for GaN power devices in the future, especially for the electric cars that will be launched in 2010, although the technology must be available by 2008.

But there is no clear consensus about the future market for CNT materials and devices. Coffee time discussions on such topics indicated some expectations that drug delivery systems and nanometer scale measurement instruments incorporating nanotubes, will be areas where this country is likely to focus resources in the future.

The next major domestic gathering of the JSAP will be at Tokyo University of Technology, 28-31 March, 2004.

**Further information about the JSAP:**
**http://www.jsap.or.jp/english/index.html**
**Government research funding agencies:**
**Ministry of Education, Culture, Sports, Science and Technology:**
**http://www.mext.go.jp/english/index.htm**
**Japan Science and Technology Corp:**
**http://www.jst.go.jp/EN/**
**New Energy and Ind. Tech. Dev. Org. :**
**http://www.nedo.go.jp/./english/index.html**